Probing Fundamental Physics in New Ways with the kSZ Effect

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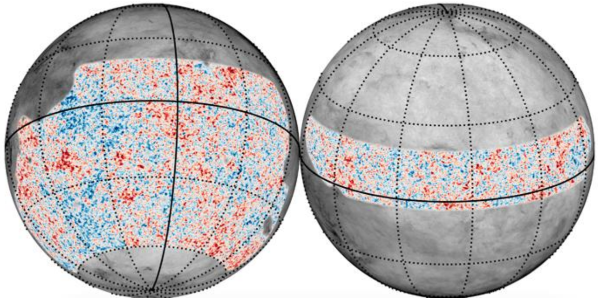
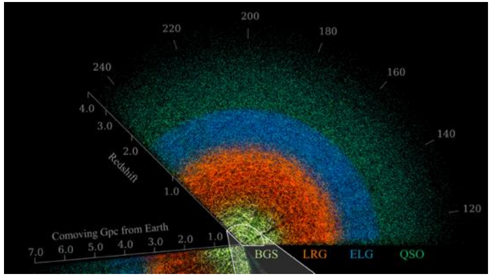


September 30, 2025 | BCCP Seminar

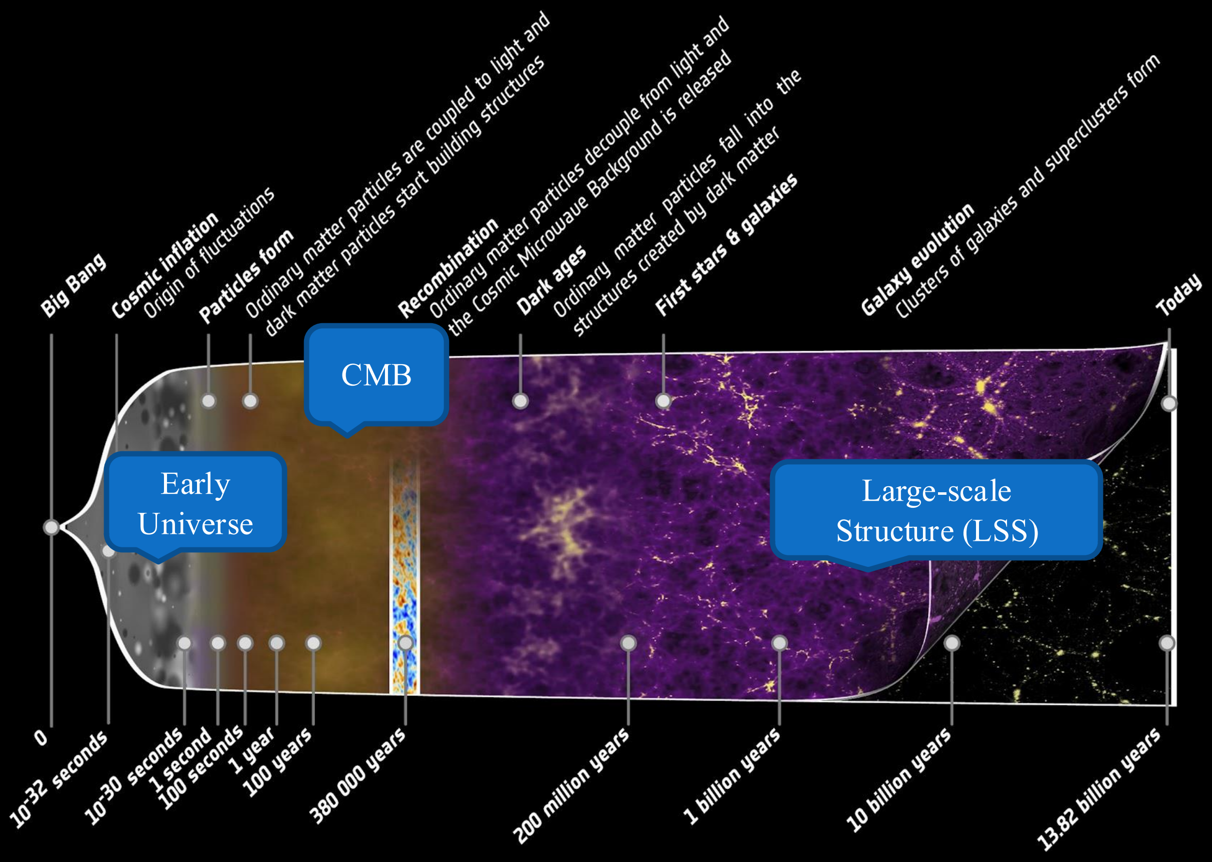


Standard model of Big Bang cosmology

Evolution of the Universe:

‘ΛCDM’ model:
- Λ: cosmological constant
- Cold Dark Matter
  + baryons

Assumes general relativity (GR) as theory of gravity

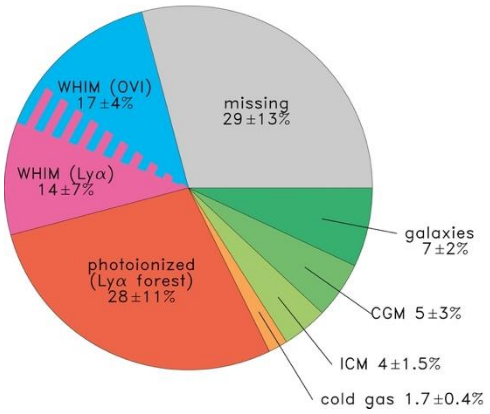


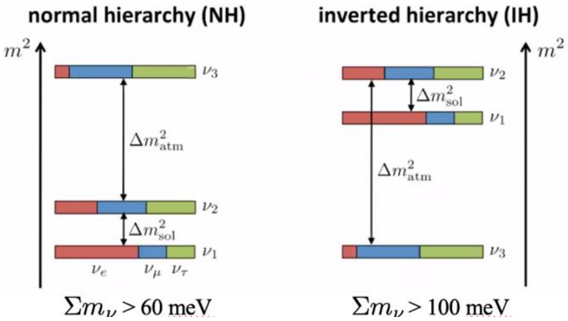
Open Questions in Physics

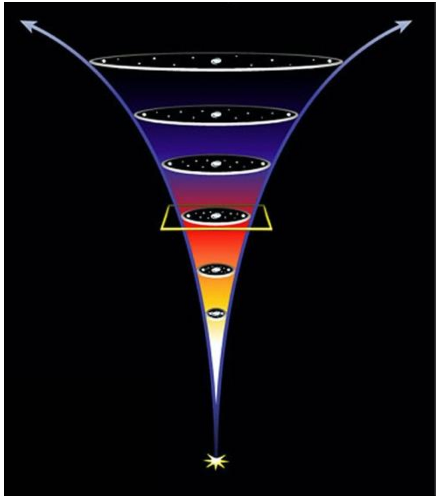
What is the abundance and distribution of baryons in the late Universe?

What is the sum of neutrino masses, and what is their mass hierarchy?

What drives the accelerated expansion, dark energy or modified gravity?







The kSZ effect

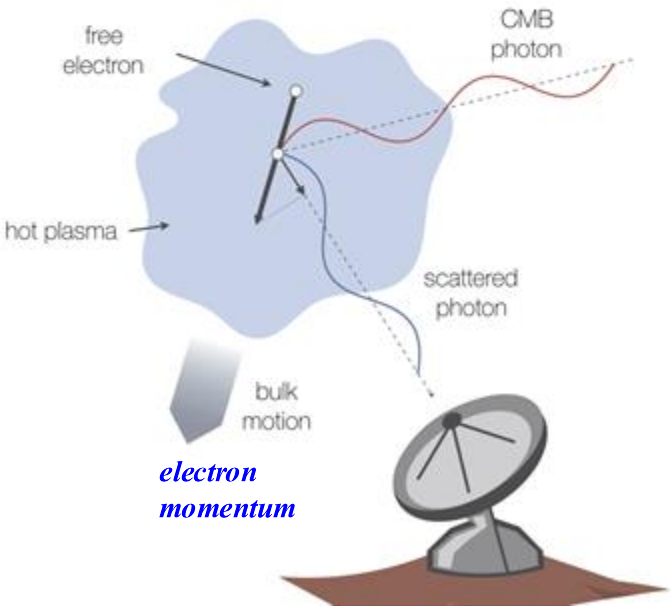
$$\Theta^{\mathrm{kSZ}}(\hat{\mathbf{n}}) = -\sigma_{\mathrm{T}} \int \frac{d\eta}{1+z} e^{-\tau} n_e(\hat{\mathbf{n}}, \eta)\, \mathbf{v_e}(\hat{\mathbf{n}}, \eta) \cdot \hat{\mathbf{n}}.$$

Astrophysics (gas density) × **Cosmology** (velocity)

- *Abundance* of baryons (z)
- *Gas density profile* ↔ galactic feedback, evolution

- Peculiar velocities → trace matter & growth rate:

  → Probe fundamental physics:
- *Neutrino masses, dark energy, gravity, f_{NL}*



electron momentum

Source: Mroczkowski+2019

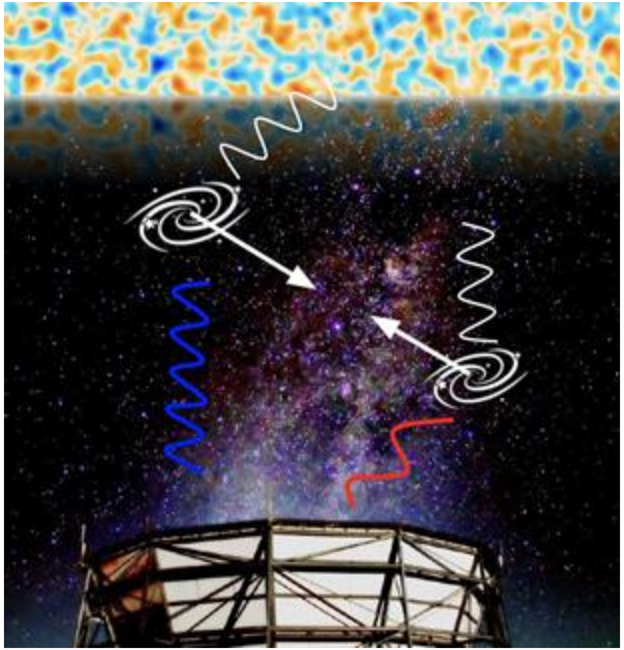
$$\mathbf{v}(\mathbf{k}) = i\frac{faH\delta(\mathbf{k})}{k}\hat{\mathbf{k}},$$

Detecting the kSZ: (how to) use LSS data?

- High-resolution CMB maps:
  ACT, SPT, → Simons Observatory (SO)!
- Cannot isolate by ILC alone

→ Estimators use **LSS** info: 3D '**tomography**' -

1. Pairwise kSZ:
   - e.g. ACT + BOSS galaxies [Hand+2012]
2. Velocity-weighted stacking:
   - e.g. ACT DR6 + DESI Y1 (photometric) LRGs [Hadzhiyska+2025]
3. Velocity reconstruction:
   - e.g. ACT DR5 + BOSS DR12 [Lague+2024]



Detecting the kSZ: (how to) use LSS data?

- High-resolution CMB maps:
  ACT, SPT, → Simons Observatory (SO)!
- Cannot isolate by ILC alone

→ Estimators use **LSS** info: 3D **'tomography'** -

1.

2.

3.

Mathematically equivalent to:

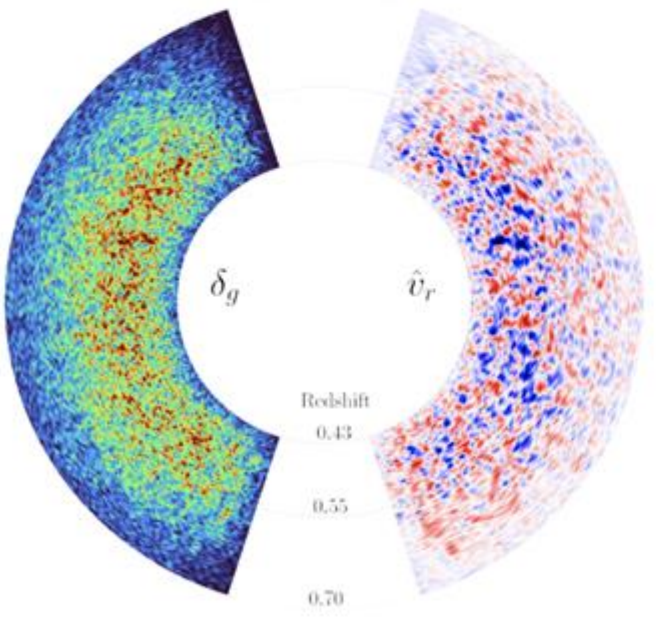
< T g g >

[Smith+18]

&

Key:

Require estimates of *individual* redshifts of galaxies



[I]

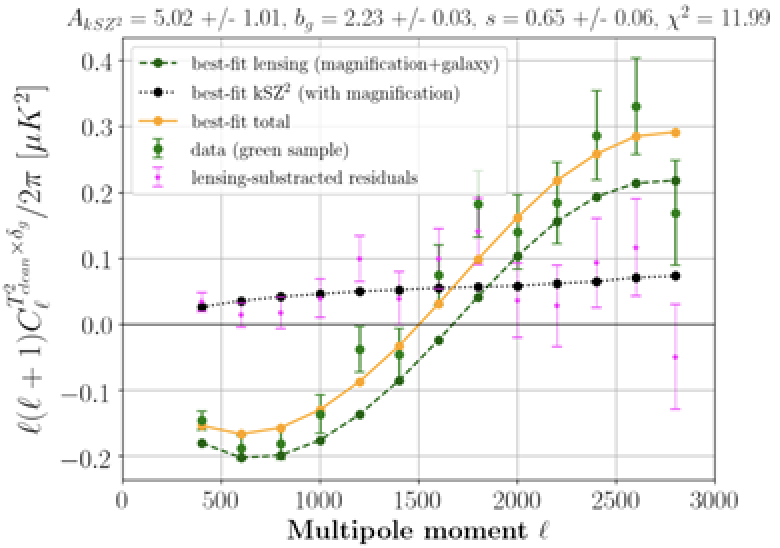
The kSZ^2 Projected-Fields Estimator

Instead: use *Projected-Fields* of LSS tracers?

$$\delta_g(\hat{\mathbf{n}}) = \int_0^{\eta_{\max}} d\eta\, W^g(\eta)\, \delta_m(\eta\hat{\mathbf{n}}, \eta)$$

- *without individual redshifts of LSS tracers*
  → only need a statistical dN/dz
- Applicable to:
  - *Photometric galaxies* - with large photo-z errors (e.g. (un)WISE, Rubin)
  - CMB/galaxy lensing convergence, quasars, 21-cm, ..
- But: $\langle \mathrm{kSZ} \times \delta_g \rangle \approx 0$
- *Solution?* $\langle \mathrm{kSZ}^2 \times \delta_g \rangle$

→ missing baryon problem



Kusiak+(2021)

Measurements in *Planck* data using WISE/unWISE galaxies

Doré+(2004); DeDeo+(2005), Ferraro+(2016), Hill+(2016), Bolliet+(2022), **Patki+(2023)**

Projected-fields '$\langle \mathrm{kSZ}^2 \times \delta_g \rangle$' estimator:

***Existing* estimator:**

Take a *cleaned* CMB map
→ Wiener filter *(f)* to select scales
→ **square** in real space
→ cross-correlate with a projected-field (LSS)

$$C_\ell^{\mathrm{kSZ}^2 \times \delta_g} = \int_0^{\eta_{\max}} \cdots$$

BUT, ***drawbacks*** -
Convolution (mixes scales)
&
Compresses across 'triangle' shapes

$$\cdots + \mathbf{q}|\eta) B_{p_{\hat{n}} p_{\hat{n}} \delta}(\mathbf{q}, -\mathbf{j} - \mathbf{q}, \mathbf{j}).$$

Key 3-pt function

\+ Picks up a significant contribution from CMB **lensing**

Doré+(2004); DeDeo+(2005), Ferraro+(2016), Hill+(2016), Bolliet+(2022), **Patki+(2023)**

Improved theoretical model of $B_{pp\delta}$

Patki, Battaglia, & Ferraro:
arXiv:2306.03127

- Accurate across **all triangle shapes**!
- **SO** & **CMB-S4**: realistic post-ILC noise.
- Galaxies: **WISE** (~50M); $z < 1$

  Rubin (~4B); $z < 3$
- Numerically compute: using emulators
- Cosmological dependence quantified:

Error on amplitude: ~1% → ~7% [*Planck* prior]

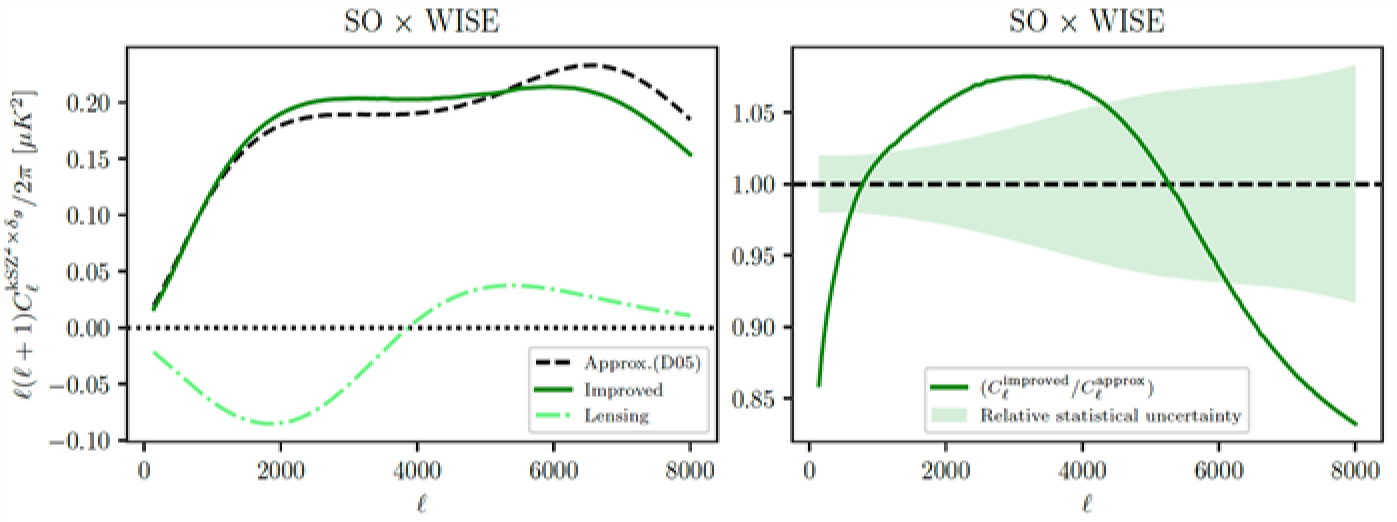
↓

Abundance of baryons

Terms	Geometric scaling
$\langle v^i(\mathbf{k})v^j(\mathbf{k}')\rangle\langle\delta(\mathbf{k}_1-\mathbf{k})\delta(\mathbf{k}_2-\mathbf{k}')\delta(\mathbf{k}_3)\rangle$	1
$\langle v^i(\mathbf{k})\delta(\mathbf{k}_1-\mathbf{k})\rangle\langle v^j(\mathbf{k}')\delta(\mathbf{k}_2-\mathbf{k}')\delta(\mathbf{k}_3)\rangle$	0
$\langle v^i(\mathbf{k})\delta(\mathbf{k}_2-\mathbf{k}')\rangle\langle\delta(\mathbf{k}_1-\mathbf{k})v^j(\mathbf{k}')\delta(\mathbf{k}_3)\rangle$	k/k_2
$\langle\delta(\mathbf{k}_2-\mathbf{k}')v^j(\mathbf{k}')\rangle\langle\delta(\mathbf{k}_1-\mathbf{k})v^i(\mathbf{k})\delta(\mathbf{k}_3)\rangle$	0
$\langle\delta(\mathbf{k}_1-\mathbf{k})v^j(\mathbf{k}')\rangle\langle v^i(\mathbf{k})\delta(\mathbf{k}_2-\mathbf{k}')\delta(\mathbf{k}_3)\rangle$	k/k_1
$\langle v^i(\mathbf{k})\delta(\mathbf{k}_3)\rangle\langle\delta(\mathbf{k}_1-\mathbf{k})\delta(\mathbf{k}_2-\mathbf{k}')v^j(\mathbf{k}')\rangle$	0
$\langle\delta(\mathbf{k}_3)v^j(\mathbf{k}')\rangle\langle\delta(\mathbf{k}_1-\mathbf{k})\delta(\mathbf{k}_2-\mathbf{k}')v^i(\mathbf{k})\rangle$	0
$\langle\delta(\mathbf{k}_1-\mathbf{k})\delta(\mathbf{k}_2-\mathbf{k}')\rangle\langle v^i(\mathbf{k})v^j(\mathbf{k}')\delta(\mathbf{k}_3)\rangle$	$[-k+(k_1 \text{ or } k_2)]/k_3$
$\langle\delta(\mathbf{k}_2-\mathbf{k}')\delta(\mathbf{k}_3)\rangle\langle v^i(\mathbf{k})v^j(\mathbf{k}')\delta(\mathbf{k}_1-\mathbf{k})\rangle$	0
$\langle\delta(\mathbf{k}_1-\mathbf{k})\delta(\mathbf{k}_3)\rangle\langle v^i(\mathbf{k})v^j(\mathbf{k}')\delta(\mathbf{k}_2-\mathbf{k}')\rangle$	0

TABLE I. The ten terms in the Wick contraction of $\langle p_\perp p_\perp \delta\rangle \sim \langle \delta \mathbf{v} \delta \mathbf{v} \delta\rangle$ which contribute to $B_{p_{\hat{n}} p_{\hat{n}} \delta}(\mathbf{k_1}, \mathbf{k_2}, \mathbf{k_3})$.

Improved modeling of the $\langle \mathrm{kSZ}^2 \times \delta_g \rangle$ signal



Bolliet+(2022)

- Total SNR $O(100)$: Significant scale-dependent differences ↔ *Gas density profile*
- Recent comparisons with simulations – match level of discrepancy (~**15%**)!

Rodriguez+(2025)

[II]

Novel < TTg > kSZ bispectrum using projected-fields

A novel $\langle \mathrm{kSZ} \times \mathrm{kSZ} \times \delta_g \rangle$ Bispectrum

Patki, Battaglia, & Hill:
arXiv: 2411.11974

Take a *cleaned* CMB map
→ Take a full **3-point** cross-correlation in
harmonic space: < TTg >
2 CMB maps with 1 **projected-field** (LSS)

- kSZ^2 estimator: convolution & compression of info
- → Binned bispectrum: **better scale separation across** 'triangle *modes*'

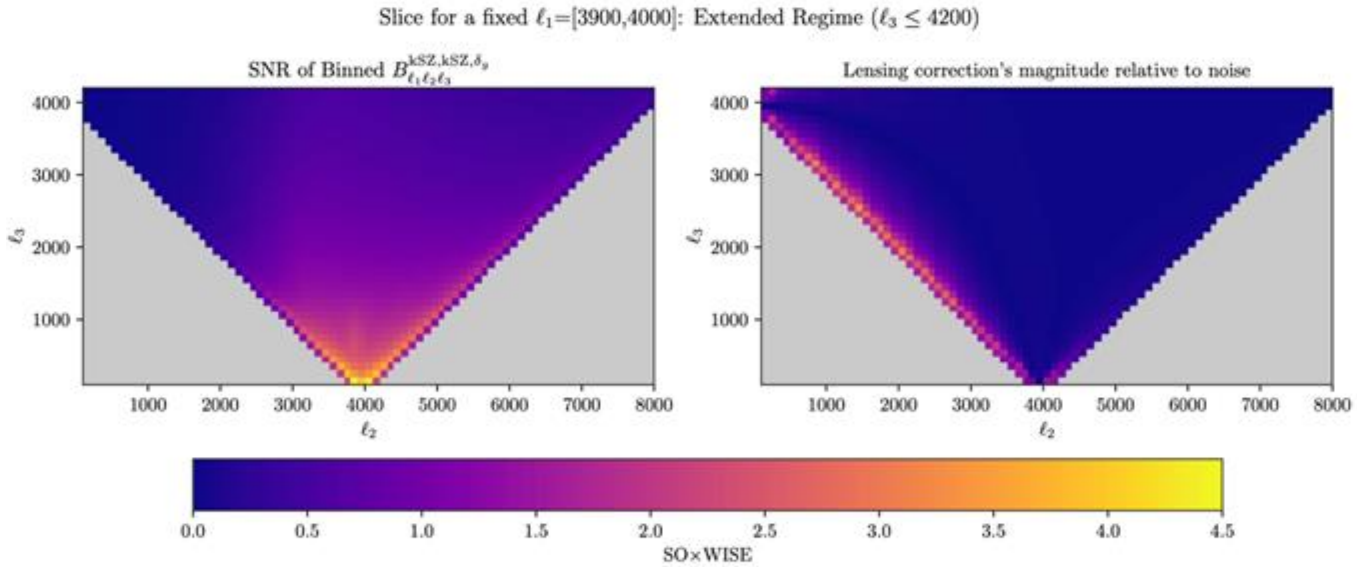
$$B^{\mathrm{kSZ,kSZ},\delta_g}_{\ell_1\ell_2\ell_3} = b(\ell_1)b(\ell_2)\int_0^{\eta_{\max}} \frac{d\eta}{\eta^4} W^g(\eta) g^2(\eta) B_{p_{\hat{n}}p_{\hat{n}}\delta}\left(\frac{\ell_1}{\eta}, \frac{\ell_2}{\eta}, \frac{\ell_3}{\eta}\right)$$

3D **Binning** in harmonic space

$$B^{\mathrm{kSZ,kSZ},\delta_g}_{abc} = \frac{\sum_{\substack{\ell_1\in\Delta_a \\ \ell_2\in\Delta_b \\ \ell_3\in\Delta_c}} \left(N_\Delta^{\ell_1\ell_2\ell_3} B^{\mathrm{kSZ,kSZ},\delta_g}_{\ell_1\ell_2\ell_3}\right)}{N_{abc}}$$

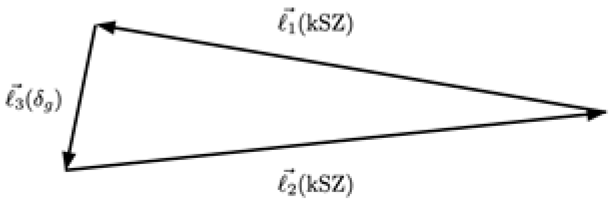
Bucher+2016, Coulton & Spergel 2019

Extended regime: Forecasts for SO×WISE



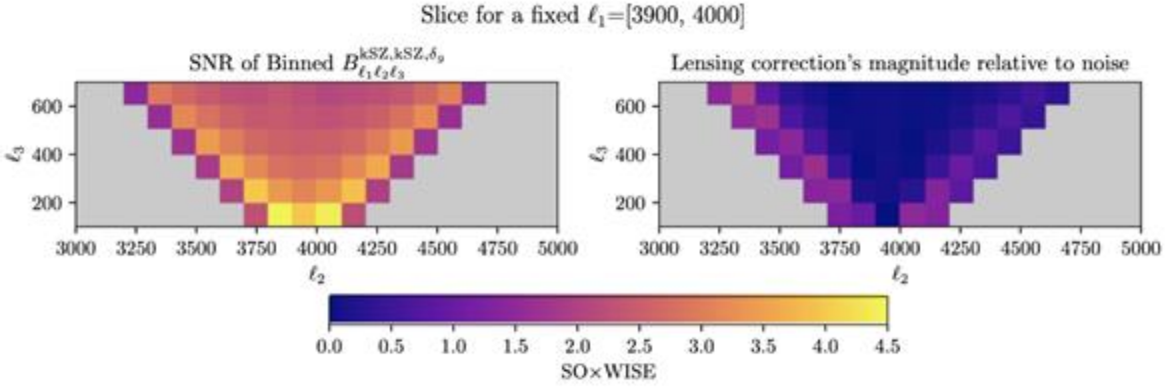
- Estimating covariance matrix analytically,

  => SNR peaks for squeezed triangles:
- Correction due to CMB lensing: relatively small



Forecasts across shapes and scales:

- Restricting LSS field to linear regime retains highest SNR modes $\ell_{\max} \sim 700$
- Robust to HOD, nonlinear bias uncertainties
- *Applications*: Constrain baryonic abundance, & potentially: gas density profile



	$B^{\mathrm{kSZ,kSZ},\delta_g}$ (default)		$B^{\mathrm{kSZ,kSZ},\delta_g}$ (extended)	
$\ell_{\max}$ of δ_g =	700		4200	
	SO × WISE	CMB-S4× WISE	SO × WISE	CMB-S4× WISE
$\mathrm{SNR_{tot}}$	106	200	221	418

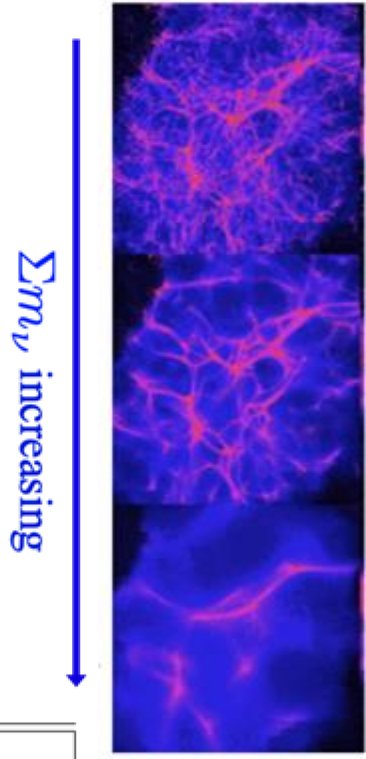
Probing Cosmology + Neutrinos

- **Degeneracy** limits inference: baryon astrophysics ↔ cosmology

Q: Can we probe scale-dependent signatures at quasilinear scales?

- Initial Fisher forecasts: ΛCDM, Σm_ν + $A \propto \tau^2$+ linear galaxy bias
- Massive neutrinos imprint the kSZ:
  suppression of clustering *and scale-dependent growth rate*

  → Complementary probe of neutrino masses!



Source: Ben Moore

	$B^{\mathrm{kSZ,kSZ},\delta_g}$ + primary CMB prior (ΛCDM)				$B^{\mathrm{kSZ,kSZ},\delta_g}$ + primary *Planck* + DESI BAO	
	Planck		(SO/CMB-S4 + LiteBIRD)			
$\sigma(\Sigma m_\nu)$	SO × WISE	CMB-S4× WISE	SO × WISE	CMB-S4× WISE	SO × WISE	CMB-S4× WISE
[meV]	159	129	97	82	54	53

[III]

Combining kSZ and CMB lensing - the E_G statistic

Is GR accurate on large scales, or should it be ‘*modified*’?

- Accelerated expansion: SNe, BAO,..
- *What drives this acceleration?*

  Dark energy (possibly dynamical), OR

  a modification of GR (MG)?

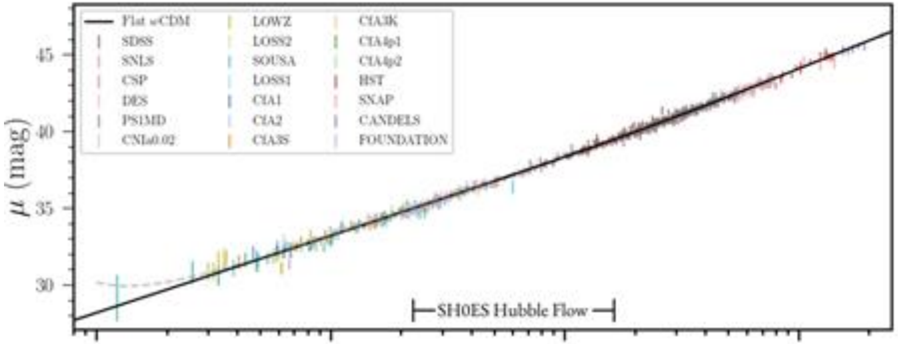
$$\nabla^2\psi = -k^2\psi = 4\pi G a^2 \mu(k,a)\rho_m(a)\delta_m$$

$$\phi = -\gamma(k,a)\psi$$

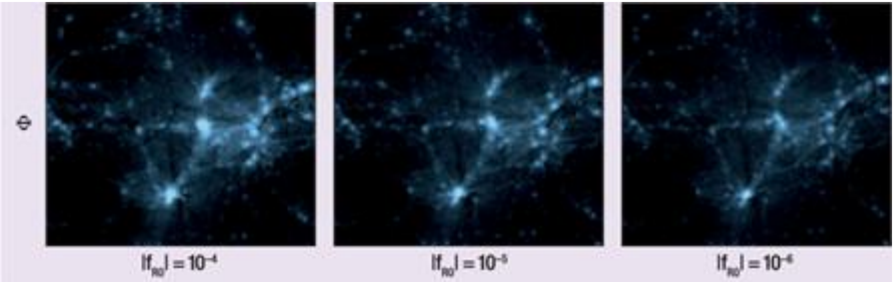
- Same expansion history; different

  growth of structure, lensing $[\nabla^2(\psi - \phi)]$

  e.g. *f(R)* gravity, Chameleon gravity, ..



Pantheon+(2022)



Source: Li (2012)

The E_G statistic: testing gravity at linear scales

$$E_G(k,z) = \frac{c\,H(z)\,[\nabla^2(\psi-\phi)]_k}{3H_0^2(1+z)^2\,k\,v(k,z)}$$

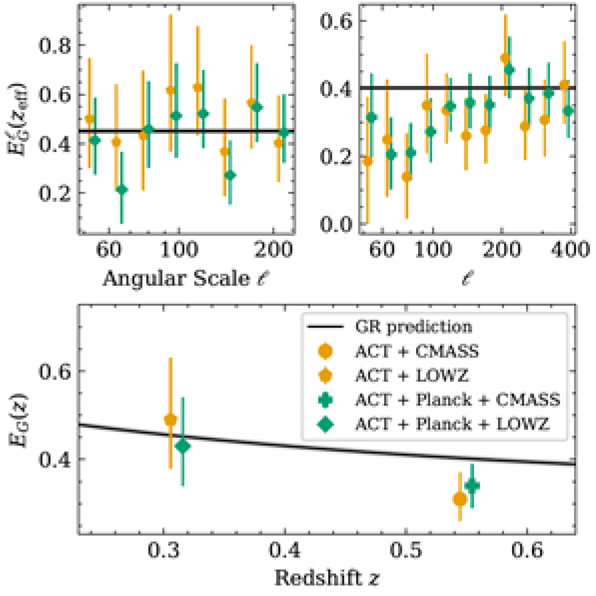
- Ratio of lensing convergence & peculiar velocity
- Expectation value in MG -

$$E_G^{\rm MG}(k,z) = \frac{\Omega_{m,0}\Sigma(k,z)}{f(k,z)}$$

$$\Sigma(k,a) \equiv \frac{1}{2}\mu(k,a)(1+\gamma(k,a))$$

- GR prediction is scale-independent!

Previously, an estimator for measuring the E_G statistic: CMB lensing, and **RSD** (for velocities).



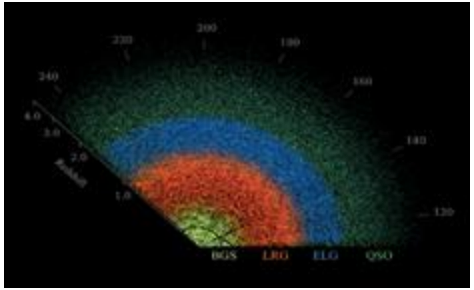
Wenzl+(2025)

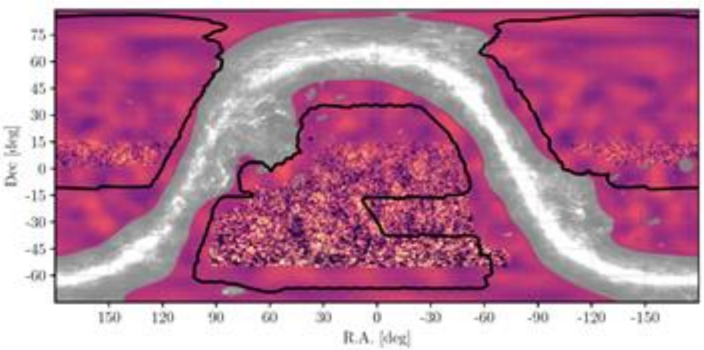
Zhang+(2007), Pullen+(2015)

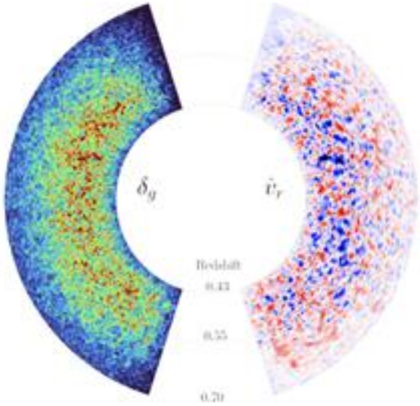
New ‘$\widehat{V}_G$’ estimator: (CMB lensing/kSZ-reconstructed velocities)

$$\widehat{V}_G(\ell, z_{\rm eff}) = \left(\frac{2c}{3H_0^2}\right) \frac{C_\ell^{\kappa g}}{\widetilde{C}_\ell^{vg\dagger}}$$

spectroscopic
galaxy
sample







- kSZ velocity-reconstruction:
  → 3D $P_{gv}(k, z_{\rm eff})$ observable
  → construct: projecting s.t. unbiased
- kSZ: better noise than RSD on largest scales

Smith+(2018)

Forecasts: combining *across scales*:

- kSZ velocity-reconstruction: 'snapshot' geometry   Smith+(2018)
- Overall, dominated by (realistic) lensing reconstruction noise
- Analytical covariance matrix:

$$\frac{\sigma^2[V_G(\ell, z_{\rm eff})]}{V_G^2(\ell, z_{\rm eff})} = \left(\frac{\sigma(C_\ell^{\kappa g})}{C_\ell^{\kappa g}}\right)^2 + \left(\frac{\sigma(\widetilde{C}_\ell^{vg^\dagger})}{\widetilde{C}_\ell^{vg^\dagger}}\right)^2$$

Preliminary

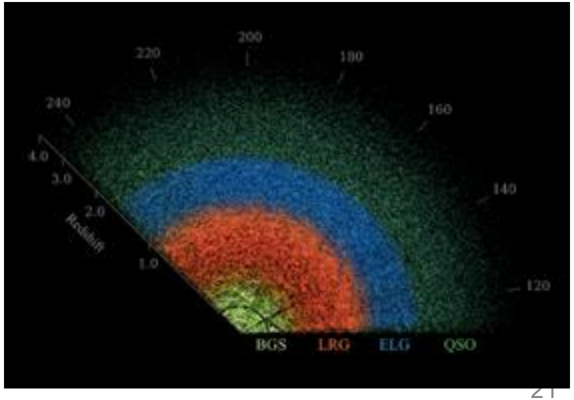
	DESI LRG	DESI ELG LOP	DESI QSO
ACT	36	32	22
SO	56	55	39

TABLE I: Cumulative SNRs of $\widehat{V}_G(\ell, z_{\rm eff})$ combined across all scales upto $k_{\max} = 0.1\ \mathrm{Mpc}^{-1}$ for different survey combinations of DESI galaxy samples and high-resolution CMB experiments.

SIMONS OBSERVATORY

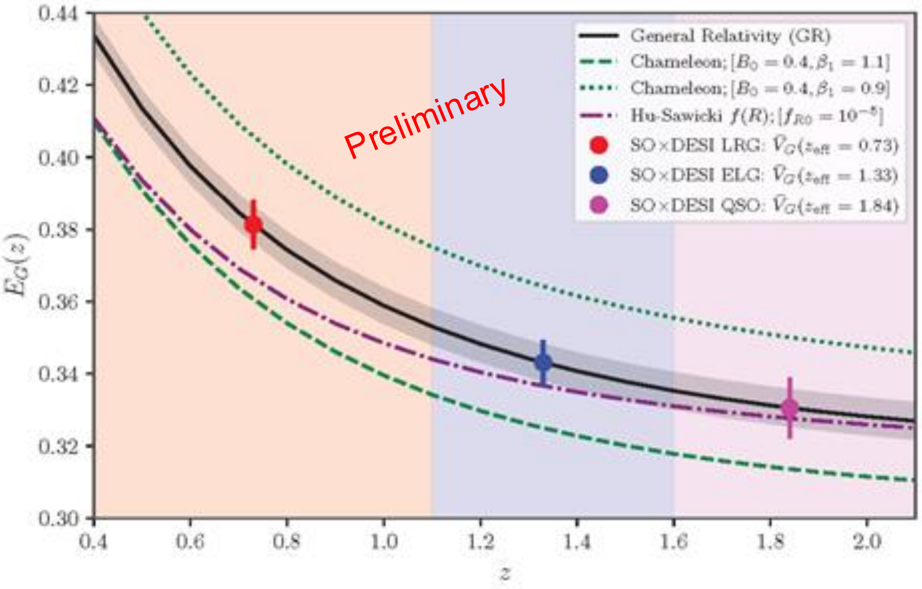
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science



Distinguishing b/w GR & MG at linear scales

Patki, Battaglia, & Bean: to appear soon on arXiv!



$$\chi^2_{\rm MG} \equiv \sum_\ell \frac{(E_G^{\rm MG}(\ell, z_{\rm eff}) - E_G^{\rm GR}(\ell, z_{\rm eff}))^2}{\sigma^2[V_G(\ell, z_{\rm eff})]}$$

Log-likelihood ratio test → SO × DESI LRGs can distinguish b/w GR and certain MG scenarios (*f(R)*, Chameleon gravity) with high confidence!

	Hu-Sawicki $f_{R0} \sim 10^{-5}$	Chameleon $(B_0 = 1.1)$	Chameleon $(B_0 = 0.9)$
ACT× DESI LRG	1.19	1.96	2.28
SO× DESI LRG	2.03	3.01	3.52

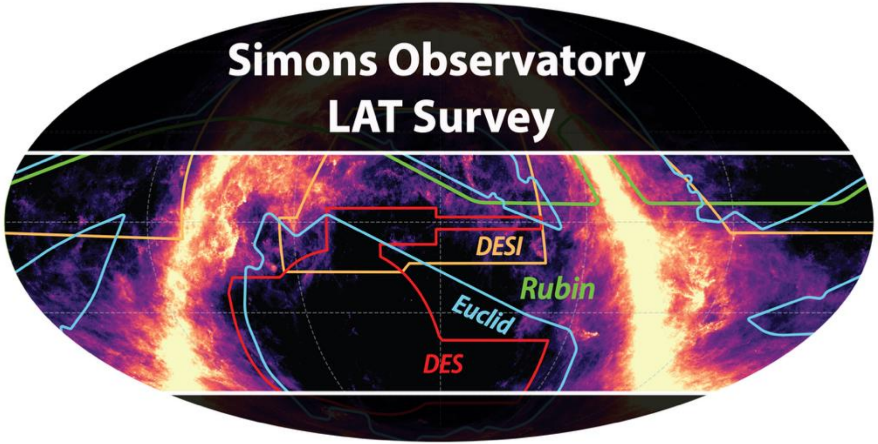
TABLE II: $\chi_{\rm rms} \equiv \sqrt{\chi^2_{\rm MG}}$ for Modified Gravity models

Future Outlook [I-III]

- Simons Observatory (LAT) is now online! → ASO → enhanced data
- Synergies: DESI, Rubin, .. Spec-S5 - including kSZ as a probe!

<u>*Interpreting upcoming measurements:*</u>

- Accurate **modeling** (baryons+theory)
- Further tests on **simulations**:
  - Residual foregrounds' impact
  - Covariance matrix
- **Pipeline** development + validation



e.g. Hotinli+(2025): kSZ velocity-reconstruction

Towards Answering Open Problems in Physics!

What is the abundance and distribution of baryons in the late Universe?

What is the sum of neutrino masses, and what is their mass hierarchy?

What drives the accelerated expansion, dark energy or modified gravity?

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Novel $< TTg >$ kSZ bispectrum

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